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# Design and Postures of a Serial Robot Composed by Closed-Loop Kinematics Chains

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## 1. Introduction

The robot presented in this chapter is a new binary hybrid (parallel-serial) type climbing system composed by several closed-chains arranged in an open-chain. The originality of the robot resides in the possibility of combining several parallel modules to build a new configuration of the robot according to the intended application. In this chapter, one possible morphology will be covered, destined to climb metallic cross-linked structures, but we will also study the kinematics and the structure of the simplest modules apart from the final robot.

Hybrid climbing robots are hard to find, but hybrid climbing robots with binary actuators are still less common. In our opinion, binary actuators are interesting, since they allow for an easier control of the robot: only two different positions need to be controlled. This advantage comes at a price, since less points in the workspace can be reached, but hereby, large motion workspace, small volume and multiple degrees of freedom will be some of the new challenges of this kind of robots (Lichter et al., 2002).

In the robot proposed in this chapter, the activation of every lineal actuator of the closed-loop generates a planar and rotational movement of the output link respect to the input one. Several parallel modules can be connected in a serial mode. In this sense, the robot is freely reconfigurable, thus, new modules (translational or rotational) can be added.

A great variety of applications can be reached with the final 2+2 closed-chain disposed in a serial mode proposed system.

As it was mentioned above, it is possible to build complex structures combining parallel modules. Attending some researches, it is not difficult to find many papers of climbing or walking robots (Qi et al., 2009; Nagakubo & Hirose, 1994; Aracil et al., 2006b), but mostly adopt serial mechanism, what makes them less robust and with compromised stability. However, few authors have researched about the use of the hybrid mechanisms to add the desired characteristics with a simple and sensor-less control (Lichter et al., 2002; Chen & Yeo, 2002; Lees & Chirikjian, 1996; Erdmann & Mason, 1988; Goldberg, 1989; Craig, 1989). The mechanism proposed combines parallel modules to set up a climbing robot, in addition with improve the mentioned characteristics, to outfit the robot with best stability and strength.

Another main feature that contributes originality compared with the related works of similar robots, it is aimed to a discrete workspace. Also we will demonstrate that it is possible to reach enough points to accomplish the required application (climb metallic

structures for inspection and maintenance tasks, construction, petroleum, bridges, etc.), and to achieve similar characteristics according to usual robots destined to these tasks.

In order to demonstrate that this robot could be used in a continuous workspace, and could be positioned in different planes and surfaces of the metallic structure, we will study the closed chain forward and inverse kinematics, and direct kinematics of the final system consisting of hybrid leg mechanism.

This chapter reviews related works, main important features and applications of some climbing and walking robots. A description of the geometry of a new developed climbing robot with a discrete hybrid (parallel-serial) moving mechanism composed by a closed kinematic chain and binary actuators will be explained. The schematic design of the robot and main postures will be also provided. Moreover, an analysis of the robot's workspace, forward and inverse kinematics of the parallel module, and forward kinematics of the complete serial robot will be also discussed.

## 2. Related work

Climbing and walking robots are common in industry applications, like as, maintenance activities of nuclear plants, oil refineries, bridges, high voltage towers, medical fields, endoscope devices, and surgical instruments in general. The applications mentioned above are practiced with some problems to access and with hazardous environmental conditions.

To accomplish these tasks, robots need some important features, as reliable or robust, to be able to move over 3D structures, including walls, ceilings, pipes or cylindrical structures (Reinoso et. al, 2001), and they also need to be adaptable into different terrains.

Parallel robots have good performance, and they are perfect to manage manipulation tasks with short manipulation cycles, high speeds and accelerations. These characteristics are very difficult to obtain in serial robots. However, the proposal system combines advantages of serial and parallel robots. For example, thanks to the linear actuators, a parallel robot has a high ratio of payload and deadweight, so using linear actuators is totally justified.

Another desirable characteristics of these robots are that they need powerful torque in the actuators, mainly if they use serial legs for climbing. Although our system uses serial legs for climbing, the combination with parallel modules does that the torque of the actuators is not needed to be very high.

Higher speed is a desirable characteristic, but it is reduced when using legs for climbing, however, in our system, velocity is not a problem because of the parallel modules that are used, similar to Stewart-Gough platforms.

Most common problem in the walking and climbing robots is how to negotiate the boundary of two plain surfaces such as convex or concave corners in 3D. In this paper, we propose a robot model that solves this problem in a right way, using hybrid legs.

The main purpose of this project was to design a very simple robot similar to the Stewart-Gough platform, but combining serial robot abilities that allowed this to do climbing tasks. Probably the most important task to solve in this robot is the control system. To solve this, it is proposed a binary actuation. The binary degrees of freedom in this system are quasi-exponential compared with serial robots, but the approach with a serial robot is increased too. As opposed, our system does not require feedback of any sensor, among other features. Some researchers have studied theses kind of binary actuation robots, but none of them has used hybrid serial-parallel technology.

Similar to parallel robots (Aracil et al., 2006a) this robot can climb the exterior and interior of tubes or metallic structures. According to the kind of structure, the end-effector and the base could carry magnetic foots or suction pads (Kim et al., 2005).

In this chapter, we do not dedicate attention to the fixation system of the end-effector and base of the robot, although a suction pad or magnetic feet are recommended. We are going to concentrate on the kinematics analysis and the postures it can achieve.

### 3. Schematic design of the robot

As it was introduced above, the main goal of this project was to assemble different parallel modules to set up some new more complex serial ones. All of the linear actuators will be binary, and they will work into ON (stretched)/OFF (shrunk) position, to accomplish a wide workspace.

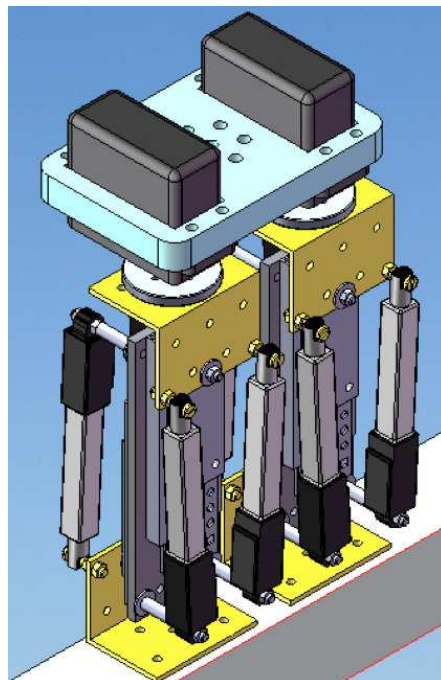


Fig. 1. Hybrid climbing robot

The purpose of this section will be the kinematics study of the closed-chain module, two closed-chain modules to set up a planar serial module, and the 2+2 closed-chain modules to set up a serial open-chain for three-dimensional movements. Another types of structures are possible to run up with the disposal and the number of the closed-chain modules.

#### 3.1 Parallel module

If we focus in the study of a simple closed-chain module, the Figure 2(a) shows such structure, that is composed by two prismatic actuated joints, with two central sliders to limit the lateral movement, and in turn a free rotational joint in the upper side to provide a rotational movement of the end-effector of the module.

As a consequence of the use of a discrete workspace, the actuated joints will be binary, and these modules will have a  $d_1$  translation and a 45 degrees rotation (Figure 2(b)), when their configuration will be  $P_1$  ON,  $P_2$  OFF or vice versa.

The Figure 2(c) refers to both actuators  $P_1$  and  $P_2$  set to ON.

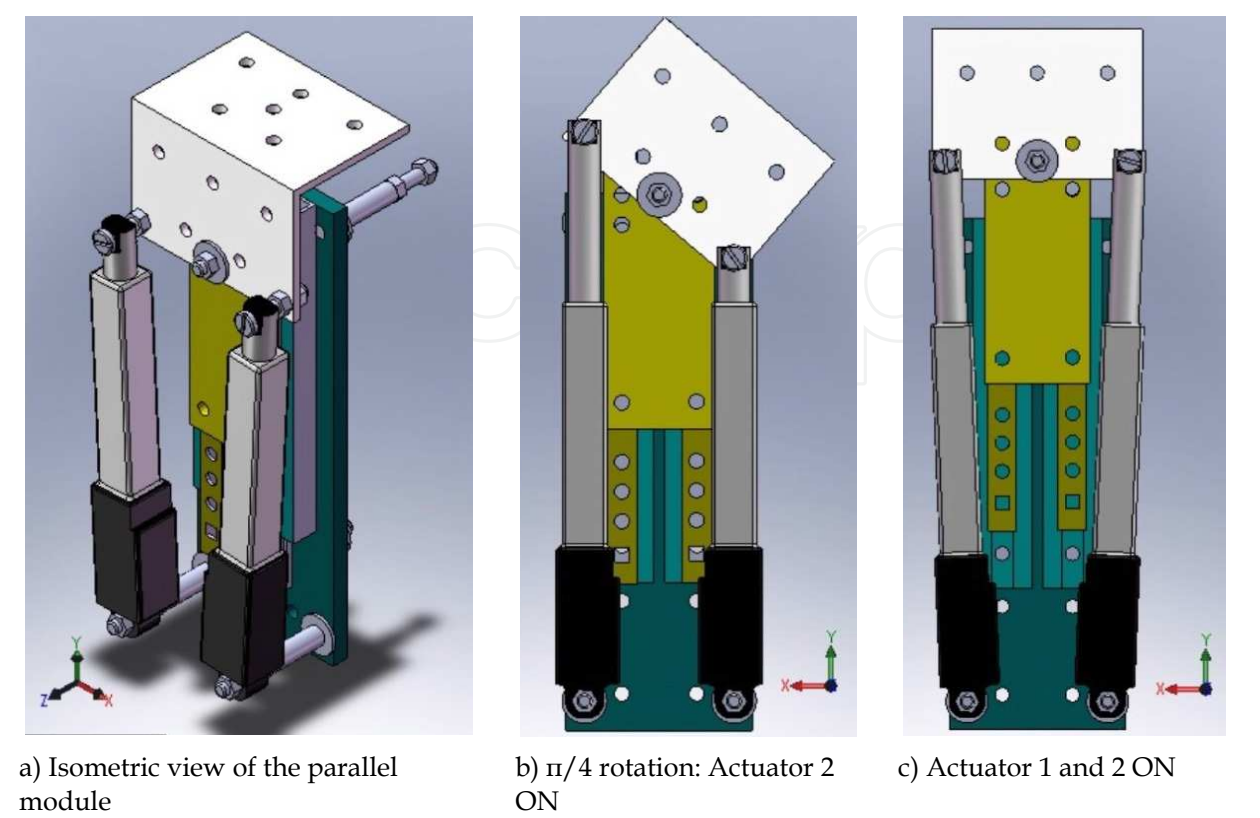


Fig. 2. Some views of the closed-chain module

Obviously, the different positions that this module is able to reach are given in Table 1:

Actuator 1	Actuator 2	Translation	Rotation
0	0	0	0°
0	1	$d_1$	45°
1	0	$d_1$	-45°
1	1	$d_2$	0°

Table 1. Positions from one parallel module

3.2 Two parallel modules disposed in a serial mode

In the Figure 3, two parallel modules can be observed. We have disposed them in a serial configuration, leaving one parallel module rotated 180 degrees and disposed in a mirror mode behind the other, to achieve robust and stable postures, and at the same time, it allows to set up 90 degrees rotations (figure 5(b)) of the end-effector around of the free joint axis. All different positions that these two attached modules are able to reach are summarized in Table 2.

In Figure 4(a), we can observe that the four linear actuators are set to off, and therefore the minimum elongation of the module is obtained. However, if we need to perform a translation around the axis of the actuators without performing a rotation of the end-effector, we could use the image configuration 4(b) with the 4 actuators set to ON. In that way, there will not be any movement induced by rotational

Actuator P1	Actuator P2	Actuator P3	Actuator P4	Translation	Rotation
0	0	0	0	0	0°
0	0	0	1	d <sub>1</sub>	-45°
0	0	1	0	d <sub>1</sub>	45°
0	0	1	1	d <sub>2</sub>	0°
0	1	0	0	d <sub>1</sub>	-45°
0	1	0	1	d <sub>1</sub> + d <sub>1</sub>	-90°
0	1	1	0	d <sub>1</sub> + d <sub>1</sub>	0°
0	1	1	1	d <sub>1</sub> + d <sub>2</sub>	-45°
1	0	0	0	d <sub>1</sub>	45°
1	0	0	1	d <sub>1</sub> + d <sub>1</sub>	0°
1	0	1	0	d <sub>1</sub> + d <sub>1</sub>	90°
1	0	1	1	d <sub>1</sub> + d <sub>2</sub>	45°
1	1	0	0	d <sub>2</sub>	0°
1	1	0	1	d <sub>2</sub> + d <sub>1</sub>	-45°
1	1	1	0	d <sub>2</sub> + d <sub>1</sub>	45°
1	1	1	1	d <sub>2</sub> + d <sub>2</sub>	0°

Table 2. Positions from two parallel modules in a serial mode

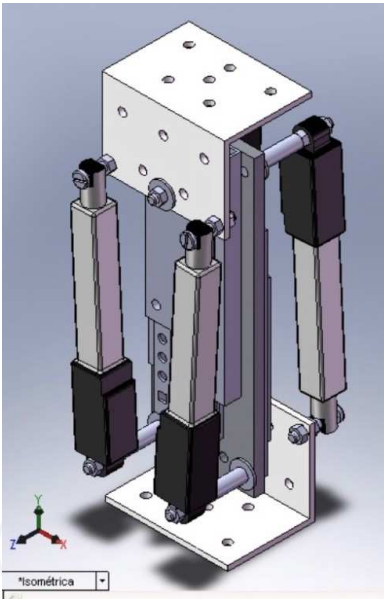


Fig. 3. Two parallel modules to draw up a serial structure

joints. In this pose, it can be observed that the central sliders indicate the distance  $d_2$  between the base and the end-effector, obviously, they will be at its highest point of stretching. However, it could be needed to reach some points in the workspace that are inclined at 90 degrees according to the base. In order to achieve this, and according to the Table 2, it could be observed in the Figure 5(b), that it can be obtained an inclination of 90 degrees, if the two mirror drives of each parallel module are switched alternately to ON and OFF. In a similar way, if a 45 degrees inclination according to the base link was needed to reach, we could perform an actuation to ON of one of the linear actuators (figure 5(a)). This could be observed in the Table 2.



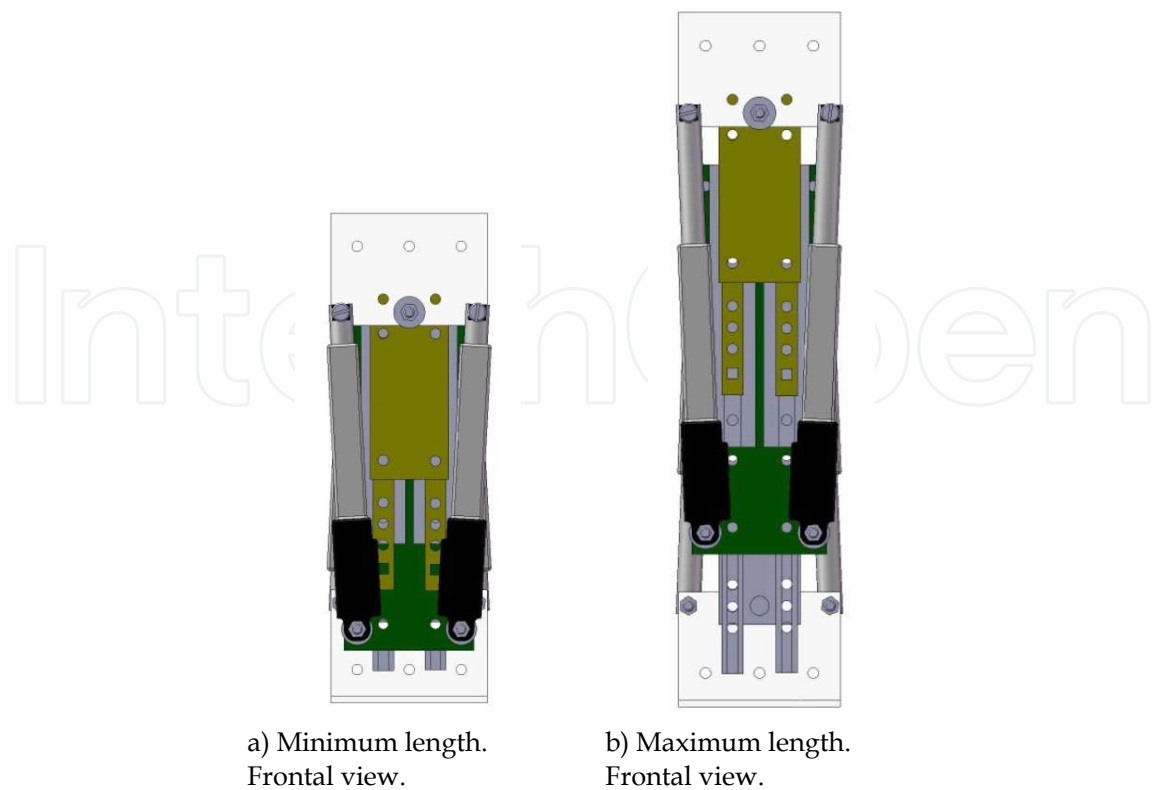


Fig. 4. Minimum and maximum prolongation of the open-chain module

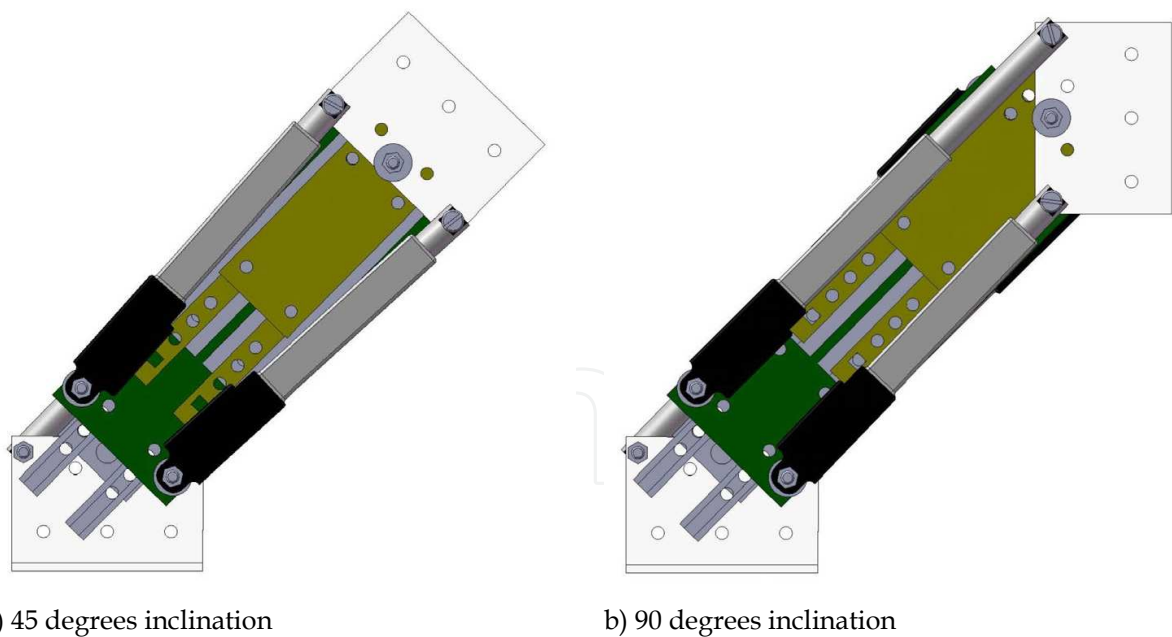


Fig. 5. Different postures of the open-chain module

3.3 2+2 Parallel modules arranged in a serial mode

As was mentioned before, the robot is composed of several parallel modules, and they are able to attach themselves in series to perform more complex structures in order to carry out a particular operation.

The robot in the Figure 1 consists of 2 + 2 parallel modules arranged to each other in a serial configuration and connected by a top link between two actuated rotational joints. According to this configuration, a three-dimensional movement of 90 and 180 degrees is possible to achieve around the rotational axis of the joint, as shown in the Table 3:

<i>Actuator R1</i>	<i>Actuator R2</i>	<i>Translation</i>	<i>Rotation</i>
0	0	0	0°
0	1	d <sub>1</sub>	90°
1	0	d <sub>1</sub>	-90°
1	1	d <sub>2</sub>	180°

Table 3. Positions of the rotational actuator

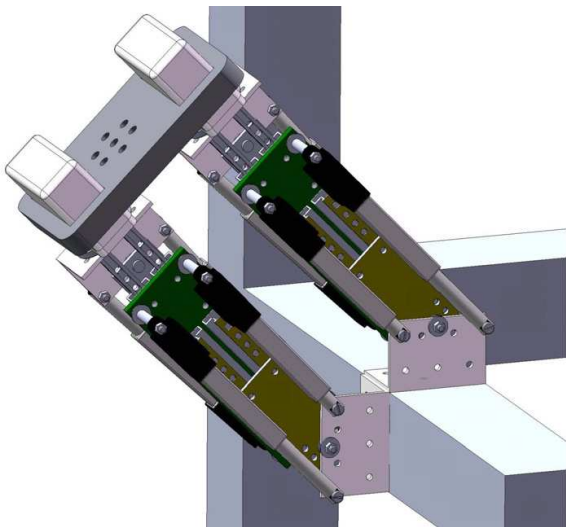


Fig. 6. Posture to a surface change of the structural frame

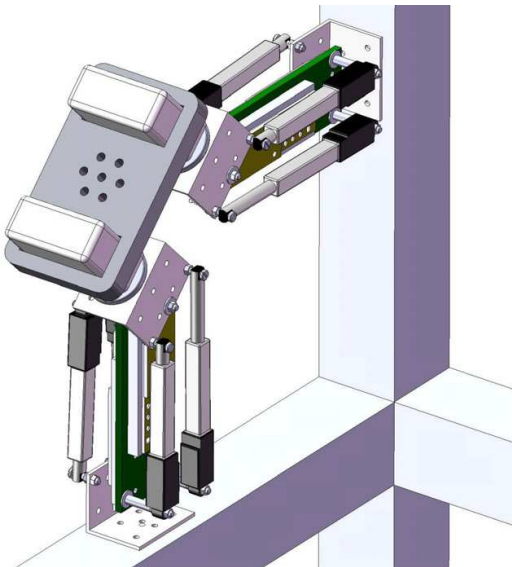


Fig. 7. Posture to evade a structural node: changing the plane



A basic problem that must be solved in the development of this robot, is that it should be able to get around structural nodes. According to the Figure 7, a posture to evade a structural node is shown. Also, the Figure 6 shows a posture to achieve a surface change. Later in this chapter, we will discuss the kinematics of the modules, so we will not focus on all possible combinations of the actuators of the robot with 2+2 parallel modules arranged in a serial mode.

## 4. Closed-chain module

### 4.1 Degrees of freedom of the module

Figure 8(a) shows a CAD model of the closed-chain, and it is composed by two active links with variable length  $l_1$  (link  $e_2$  with  $e_3$ ) and  $l_2$  (link  $e_4$  with  $e_5$ ), and two passive links,  $e_1$  and  $e_6$ , with fixed length  $2a_1$  and  $2a_2$ , respectively. A slider keeps the midpoint of the upper passive link  $e_6$  on the line  $x=a_1$ . There is a fixed link  $e_1$ , four revolute joints (1, 3, 5 and 7) and two prismatic joints (2 and 6).

According to the Grübler criterion (Grübler, 1883), the number of active degrees of freedom is given by:

$$F = \lambda(n - j - 1) + \sum_i f_i \quad (1)$$

where:

- $n$ , the number of links in the mechanism, including the fixed link (from  $e_1$  to  $e_7$ ):

$$n = 7 \quad (2)$$

- $\lambda$ , degrees of freedom of the space (planar) in which the mechanism is intended to work:

$$\lambda = 3 \quad (3)$$

- $j_1$ , number of prismatic joints

$$j_1 = 3 \quad (4)$$

- $j_3$ , number of revolute joints

$$j_3 = 5 \quad (5)$$

- $f_i$ , DoF permitted by revolute or prismatic joint  $i$

$$f_i = 1 \quad (6)$$

replacing (2), (3), (4), (5), (6) in (1)

$$F = 3(7 - 8 - 1) + 5 * 1 + 3 * 1 = 2 \quad (7)$$

These Grübler criterion results could be represented with an equivalent model (figure 8(b)) composed by a prismatic joint plus a solidary revolute joint, that represents reliably the model of figure 8(a). In this model, the P part represents the 3D prismatic joint and the R part represents the 3D revolute joint. The total distance traveled by the slider is equivalent to the prismatic joint distance  $d$  of figure 8(a).

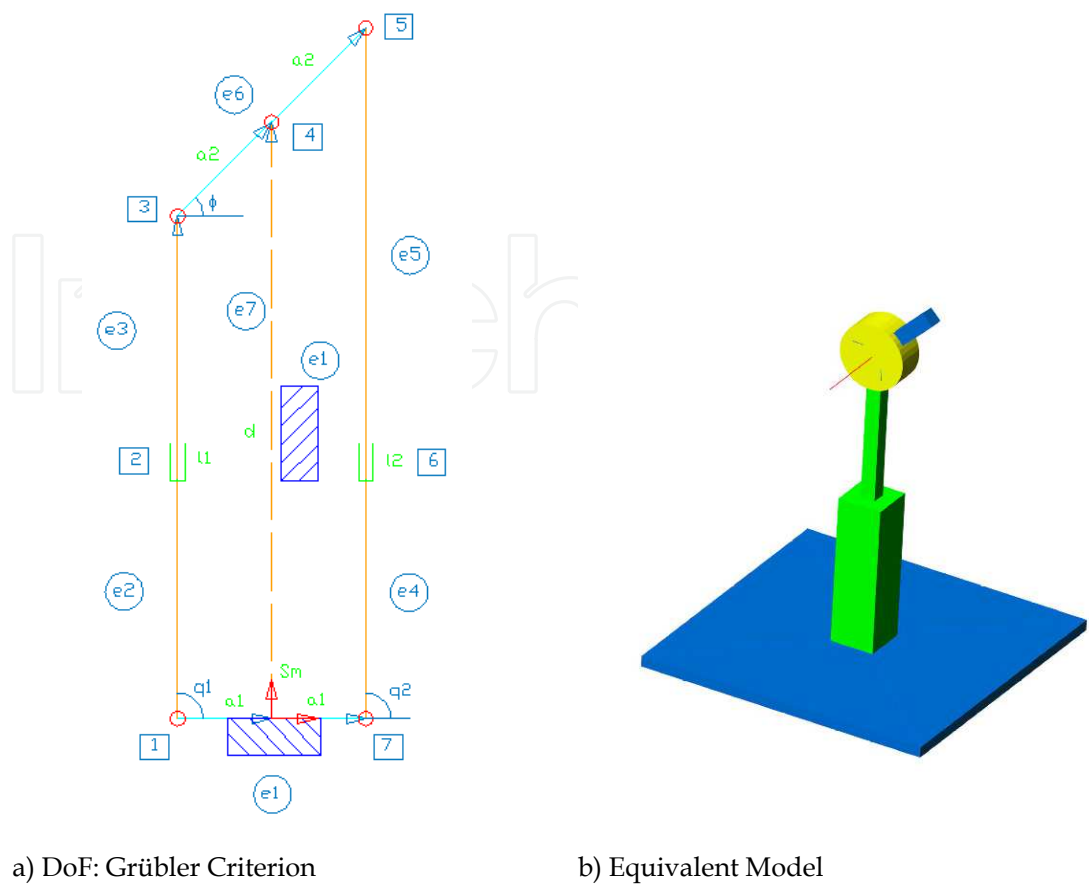


Fig. 8. Closed-chain module

4.2 Inverse kinematics of the parallel module

To study the inverse kinematics of the parallel module of the robot, a series of vectorial equations have been defined to estimate the position and orientation of the base according to the length of the linear actuators and the rotational angles of the rotational joints. Inverse kinematics pretends to solve the position of the link  $e_6$  of figure 8(a) according to a reference system  $S_m$  that is solidary to the ground link. It could be defined as a translation  $d$  and a rotation  $\phi$ . In this way, inverse kinematics proposes to solve (11, 12) as a function of ( $d$ ,  $\phi$ ) parameters. We could define a movement for the parallel module in different alternative ways. In the next one it is indicated that the mid point of the  $e_6$  link should be at the position ( $a_1$ ,  $d$ ) according to the reference system  $S_m$  solidary to the ground link. According to the figure 8(a), two vectorial equations are obtained:

$$\vec{a_1} + \vec{d} = \vec{a_2} + \vec{l_1} \tag{8}$$

$$\vec{a_1} + \vec{l_2} = \vec{d} + \vec{a_2} \tag{9}$$

where, a restriction on  $e_6$  or  $d$  link can be observed, because this vector angle will be always  $90^\circ$  according to the ground link  $a_1$ . Through a vectorial decomposition of the equations (8), (9), (10) and (11) these new equations are obtained:

$$a_1 = a_2 \cos(\phi) + l_1 \cos(q_1) \quad (10)$$

$$d = l_1 \sin(q_1) + a_2 \sin(\phi) \quad (11)$$

$$a_1 + l_2 \cos(q_2) = a_2 \cos(\phi) \quad (12)$$

$$l_2 \sin(q_2) = d + a_2 \sin(\phi) \quad (13)$$

and with a new disposition of the equations:

$$a_1 = l_1 \cos(q_1) + a_2 \cos(\phi) \quad (14)$$

$$d = l_1 \sin(q_1) + a_2 \sin(\phi) \quad (15)$$

$$-a_1 = l_2 \cos(q_2) - a_2 \cos(\phi) \quad (16)$$

$$d = l_2 \sin(q_2) - a_2 \sin(\phi) \quad (17)$$

it could be obtained  $l_1$  link length based on  $d$  and  $\phi$  from (14) and (15) equations:

$$(a_1 - a_2 \cos(\phi))^2 = (l_1 \cos(q_1))^2 \quad (18)$$

$$(d - a_2 \sin(\phi))^2 = (l_1 \sin(q_1))^2 \quad (19)$$

where the addition of both of them:

$$(a_1 - a_2 \cos(\phi))^2 + (d - a_2 \sin(\phi))^2 = l_1^2 \cos^2(q_1) + l_1^2 \sin^2(q_1) \quad (20)$$

and in the next step we will find the value of  $l_1$ , in order that  $q_1$  disappears from the equation:

$$l_1 = +\sqrt{(a_1 - a_2 \cos(\phi))^2 + (d - a_2 \sin(\phi))^2} \quad (21)$$

Likewise, for  $l_2$ :

$$l_2 = +\sqrt{(-a_1 + a_2 \cos(\phi))^2 + (d + a_2 \sin(\phi))^2} \quad (22)$$

Only positive solutions are of interest for  $(l_1, l_2)$ . As well, looking at the equations, with a pair  $(d, \phi)$ , a unique pair  $(l_1, l_2)$  is obtained and, backwards, with  $(l_1, l_2)$  a unique pair  $(d, \phi)$  is obtained too.

#### 4.3 Forward kinematics of the parallel module

Forward kinematics problem has been solved with a numerical method based on least squares method.

The equations (14), (15), (16) and (17) don't allow to find the value of  $\phi$  and  $d$  as a length  $l_1$  and  $l_2$  function, because  $q_1$  and  $q_2$  are themselves function of  $d$  and  $\phi$ .

We are going to set out the Levenberg-Marquardt numerical method (Levenberg, 1944), (Marquardt, 1963) so the equations (14), (15), (16) and (17) should be redefined as:

$$a_1 = l_1 \cos(q_1) + a_2 \cos(\phi) \quad (23)$$

$$0 = l_1 \sin(q_1) + a_2 \sin(\phi) - d \quad (24)$$

$$-a_1 = l_2 \cos(q_2) - a_2 \cos(\phi) \quad (25)$$

$$0 = l_2 \sin(q_2) - a_2 \sin(\phi) - d \quad (26)$$

An optimization process could be defined with the next functions:

$$f_1(\vec{s}) = l_1 \cos(q_1) + a_2 \cos(\phi) \quad (27)$$

$$f_2(\vec{s}) = l_1 \sin(q_1) + a_2 \sin(\phi) - d \quad (28)$$

$$f_3(\vec{s}) = l_2 \cos(q_2) - a_2 \cos(\phi) \quad (29)$$

$$f_4(\vec{s}) = l_2 \sin(q_2) - a_2 \sin(\phi) - d \quad (30)$$

defining:

$$\vec{f} = \begin{bmatrix} f_1(\vec{s}) \\ f_2(\vec{s}) \\ f_3(\vec{s}) \\ f_4(\vec{s}) \end{bmatrix} \quad (31)$$

where the state vector  $\vec{s}$  is defined as:

$$\vec{s} = \begin{bmatrix} d \\ \phi \\ q_1 \\ q_2 \end{bmatrix} \quad (32)$$

and the constraints vector:

$$\vec{y} = \begin{bmatrix} a_1 \\ 0 \\ -a_1 \\ 0 \end{bmatrix} \quad (33)$$

Wherewith, the problem is raised as a minimization of the function:

$$F(\vec{s}) = \sum_{i=1}^4 \left( f_i(\vec{s}) - y_i \right)^2 \quad (34)$$

For the minimization, we could raise an initial solution  $\vec{s}_0$  and update in the direction of the gradient  $\frac{\partial J}{\partial s}$

$$\vec{s}_{k+1} = \vec{s}_k + \delta \quad (35)$$

with:

$$\delta = (JJ^T)^{-1} J^T (\vec{y} - \vec{f}) \quad (36)$$

where J is the Jacobian matrix of the robot.

For the algorithm converging, it must indicate an initial solution of the  $\vec{s}$ . An approximation in order to achieve good results is:

$$d_0 = \frac{l_1 + l_2}{2} \quad (37)$$

$$\phi_0 = \frac{l_2 + l_1}{2a_2} \quad (38)$$

$$q_{10} = \arctan \frac{d_0 - a_2 \sin \phi_0}{a_1 - a_2 \cos \phi_0} \quad (39)$$

$$q_{20} = \arctan \frac{d_0 + a_2 \sin \phi_0}{-a_1 + a_2 \cos \phi_0} \quad (40)$$

The Jacobian matrix is calculated as follows:

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial d} & \frac{\partial f_1}{\partial \phi} & \frac{\partial f_1}{\partial q_1} & \frac{\partial f_1}{\partial q_2} \\ \frac{\partial f_2}{\partial d} & \frac{\partial f_2}{\partial \phi} & \frac{\partial f_2}{\partial q_1} & \frac{\partial f_2}{\partial q_2} \\ \frac{\partial f_3}{\partial d} & \frac{\partial f_3}{\partial \phi} & \frac{\partial f_3}{\partial q_1} & \frac{\partial f_3}{\partial q_2} \\ \frac{\partial f_4}{\partial d} & \frac{\partial f_4}{\partial \phi} & \frac{\partial f_4}{\partial q_1} & \frac{\partial f_4}{\partial q_2} \end{bmatrix} = \begin{bmatrix} 0 & -a_2 \sin \phi & -l_1 \sin q_1 & 0 \\ -1 & a_2 \cos \phi & l_1 \cos q_1 & 0 \\ 0 & a_2 \sin \phi & 0 & -l_2 \sin q_2 \\ -1 & -a_2 \cos \phi & 0 & l_2 \sin q_2 \end{bmatrix} \quad (41)$$

In the performed tests in order to solve forward kinematics, the algorithm converges to the correct solution in only two iterations, with an  $F < 0.0001$  error.

Others ways to find the value of  $\delta$  could be probed, like:

$$\delta = (JJ^T + \lambda I)^{-1} J^T (\vec{y} - \vec{f}) \quad (42)$$

where  $\lambda$  permits to regulate the speed as the function converges. Another way is:

$$\delta = (JJ^T + \lambda \text{diag}(J^T J))^{-1} J^T (\vec{y} - \vec{f}) \quad (43)$$

this is known as the Levenberg-Marquardt algorithm.

## 5. Forward kinematics of the open-chain module

According to the Subsection 3.3 a 2+2 parallel modules disposed in a serial structure could be set up. We are going to start from a complete serial model of the robot. The Figure 1 shows this set up of the robot. An equivalent model is shown in the Figure 9.

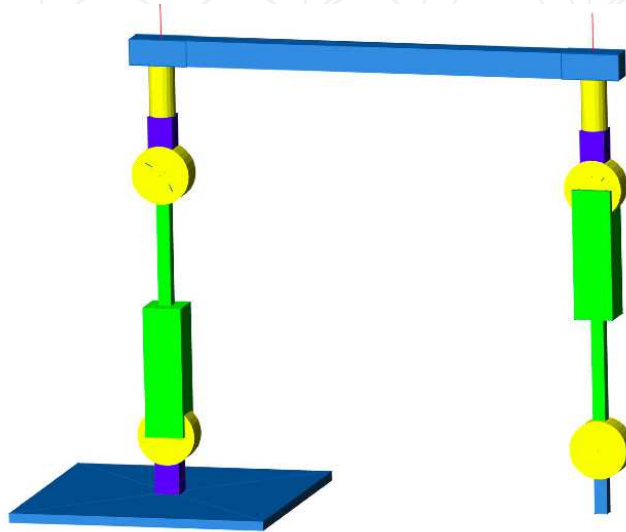


Fig. 9. 3D model of the serial robot

To solve forward kinematics of the open-chain, Denavit-Hartenberg algorithm (Denavit & Hartenberg, 1955; Uicker et al., 1964; Hartenberg & Denavit, 1964) has been used. In order to solve transformation matrices, *The Robotics Toolbox for Matlab* (Corke, 1996) has been used. Firstly, and following D-H convention, we could establish the coordinate axes as follows in the Figure 10. Secondly, the transformation matrix will be solved:

$${}^0T_1 = \begin{bmatrix} -\sin\phi_1 & 0 & \cos\phi_1 & 0 \\ \cos\phi_1 & 0 & \sin\phi_1 & 0 \\ 0 & 1 & 0 & H_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (44)$$

$${}^1T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (45)$$

$${}^2T_3 = \begin{bmatrix} \cos\phi_3 & 0 & \sin\phi_3 & 0 \\ \sin\phi_3 & 0 & -\cos\phi_3 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (46)$$



$${}^3T_4 = \begin{bmatrix} \cos \phi_4 & -\sin \phi_4 & 0 & \cos \phi_4 * H_4 \\ \sin \phi_4 & \cos \phi_4 & 0 & \sin \phi_4 * H_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{47}$$

$${}^4T_5 = \begin{bmatrix} \cos \phi_5 & 0 & -\sin \phi_5 & 0 \\ \sin \phi_5 & 0 & \cos \phi_5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{48}$$

$${}^5T_6 = \begin{bmatrix} \cos \phi_6 & 0 & -\sin \phi_6 & 0 \\ \sin \phi_6 & 0 & \cos \phi_6 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{49}$$

$${}^6T_7 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & L_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{50}$$

$${}^7T_8 = \begin{bmatrix} \cos \phi_8 & 0 & -\sin \phi_8 & 0 \\ \sin \phi_8 & 0 & \cos \phi_8 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{51}$$

Below, the Table 4 indicates the D-H Parameters of the 8 DoF of the model:

Joint	$\phi$	$d$	$a$	$\alpha$
1R	$\phi_1+90^\circ$	H <sub>1</sub>	0	90°
2R	0	L <sub>2</sub>	0	-90°
3R	$\phi_3$	0	0	90
4R	$\phi_4$	0	H <sub>4</sub>	0
5R	$\phi_5$	0	0	-90
6R	$\phi_6$	0	0	-90
7R	0	L <sub>6</sub>	0	90
8R	$\phi_8$	0	0	-90

Table 4. D-H Parameters table of the serial model

## 6. Robot workspace

A preliminary study of the workspace that could reach a set up of 2+2 parallel modules arranged in a serial mode, with actuated rotational joints, have been performed. The goal was to check if it was able to climb a three-dimensional cross-linked structure.

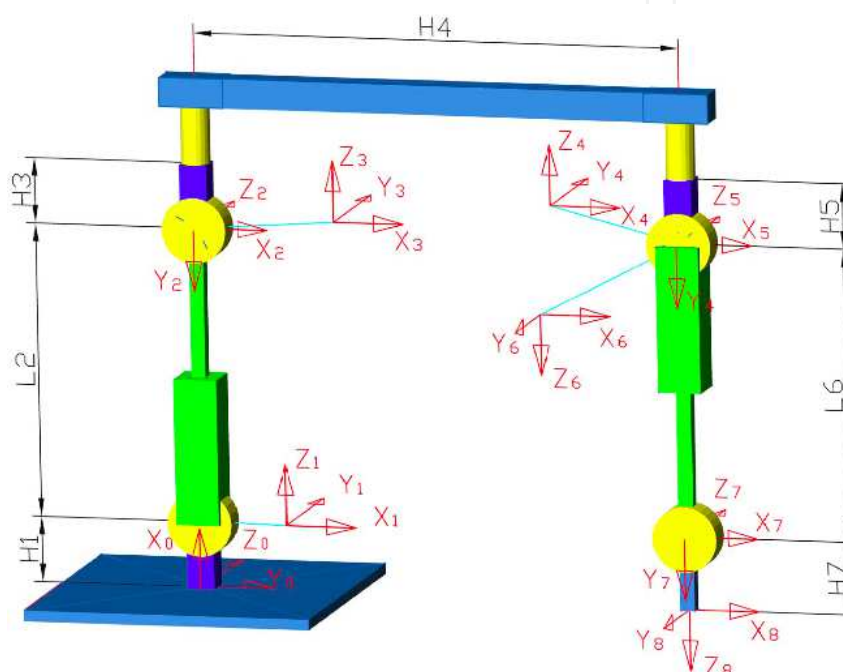


Fig. 10. 3D model of the serial robot with D-H convention axis

For one of the possible workspaces, some of the mathematical combinations of the robot actuators have been obtained, and a vector with all of them has been generated. This vector has been used to obtain different final points of the end-effector. Therefore, every element of the vector will be every final point of the previously described.

We have obtained a  $2^{10}$  elements vector (Figure 11) as a result of the ten joints of the real model. In this vector, the interferences between links were not taken into consideration.

On the other hand, a cross-linked structure and a robot model have been simulated through SolidWorks. The goal was to check if the robot was able to reach enough workspace points and, at the same time, to perform a plane change in the cross-linked structure, and all of this has been shown in the Figures 6 and 7 with the simulated model.

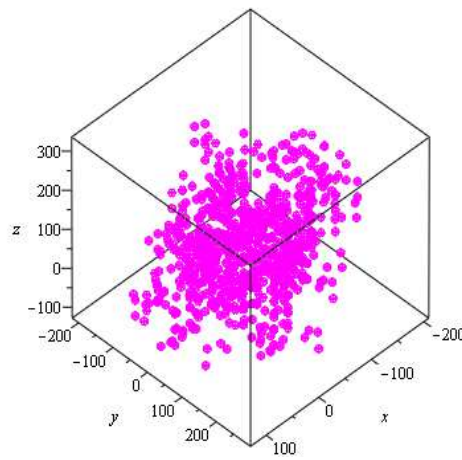


Fig. 11. 1024 points work space

## 7. Conclusions

Some years ago, new robotic devices with a large number of degrees of freedom and binary actuators were developed to achieve a large motion workspace, to be capable of large fine motion, and have a small-stowed volume. Applications as inspection and maintenance tasks require them to adapt the robot to this kind of hostile environment.

In this way, a new reconfigurable binary climbing robot with closed-chains disposed in an open-chain architecture, has been presented.

Related works has been reviewed at the Section 2, as well as important features and applications of some climbing and walking robots.

Sometimes, the kinematics solution of parallel mechanisms requires using redundant sensors to establish a control loop because it becomes quite complicated. In this chapter, a binary actuators solution is presented, so a sensor-less feature is included.

Linear actuators are directly connected to the base and to the end-effector of the parallel modules, so these actuators are at the same time structural elements of the complete serial robot, and they work in a simultaneous way, which gives them the ability to handle loads much greater than its own weight.

The schematic design of the robot, description of the geometry and main postures have been also provided in the Section 3. In this Section, also has been studied in an independent way the parallel module, the two parallel modules disposed in a serial mode, and the complete robot composed by 2+2 Parallel modules arranged in a serial mode.

Moreover, an analysis of the forward and inverse kinematics of the parallel module, and forward kinematics of the complete serial robot are discussed in the Sections 4 and 5.

Finally the discrete workspace of the robot has been represented in the Section 6.

Future works will consist on determine the inverse kinematics solution of the serial robot, to implement the control system and applying path-planning algorithms to move the robot around of the cross-linked structure.

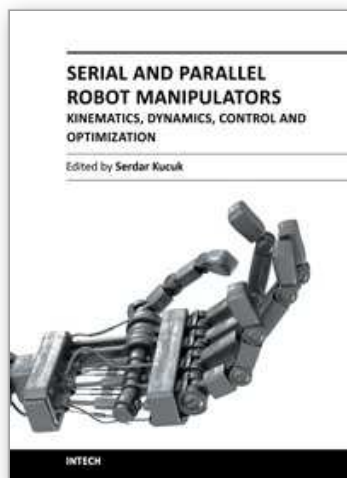
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## **Serial and Parallel Robot Manipulators - Kinematics, Dynamics, Control and Optimization**

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The robotics is an important part of modern engineering and is related to a group of branches such as electric & electronics, computer, mathematics and mechanism design. The interest in robotics has been steadily increasing during the last decades. This concern has directly impacted the development of the novel theoretical research areas and products. This new book provides information about fundamental topics of serial and parallel manipulators such as kinematics & dynamics modeling, optimization, control algorithms and design strategies. I would like to thank all authors who have contributed the book chapters with their valuable novel ideas and current developments.

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